Comparison of the static frictional resistance and surface topography of ceramic orthodontic brackets: an in vitro study

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Objectives: The aim of this study was to investigate the frictional resistance (FR) and surface topography of newly available polycrystalline alumina (PCA) ceramic brackets characterised by a yttria-stabilised zirconia (YSZ) coating of the slots, compared with monocrystalline alumina (MCA) ceramic brackets and stainless steel (SS) brackets.

Methods: The FR was investigated using a universal testing machine. The test groups included PCA (Clarity Advanced, 3M Unitek, CA, USA) and MCA (Inspire Ice, Ormco, CA, USA). The control group included SS brackets. A sliding test was performed for each bracket type with three bracket-wire angulations (0°, 5°, 10°). A total of 225 sliding tests were performed in a dry environment, and 225 tests were performed in a wet environment of artificial saliva. A scanning electron microscope was used for qualitative assessments. The surface topography of the bracket slots was quantitatively assessed using an optical profilometer.

Results: In the dry environment, the overall FR values were significantly lower for PCA and SS brackets compared with MCA brackets ($p < 0.001$), but no significant difference was found between PCA and SS brackets. In the wet environment, there were no significant differences between the bracket groups and their overall FR values. There was a significant correlation between the overall FR and the bracket-wire angulation values ($p < 0.001$). The bracket slot surface topography revealed that the PCA bracket slots had the highest roughness values, followed by SS and MCA brackets ($p < 0.001$). There was no significant correlation between the roughness values of the bracket slots and the FR in a passive configuration for all bracket types.

Conclusion: A yttria-stabilised zirconium coating of the PCA ceramic bracket slots might be a positive approach to apply for the reduction of FR.

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Introduction

The main treatment goal of orthodontics is to improve the aesthetic appearance of the teeth. As society has become more health conscious, there has been an increased demand from patients for aesthetic orthodontic appliances (ceramic brackets, lingual appliances, and clear aligners), especially from the growing number of adults seeking treatment.

Friction has been defined as the force that opposes the movement of two objects sliding over each other.[1,2] The force of friction is generated in a direction opposite to the movement force and is proportional to the force transmitted across the plane of contact.[1,2] The frictional force or resistance to orthodontic sliding (RS) is constantly present between the bracket and the archwire, and produces resistance against any force applied to move the teeth.[3] The loss of applied force due to frictional resistance (FR) has been estimated by several studies and was found to range from 12% to more than 70% in certain cases.[3-6] FR is multifactorial in nature, which contemporary studies have divided into physical and biological determinants. The physical factors are related to the characteristics of

Table I. Sample description.

Material	Product	Dimensions (inches)	Group observations	Total observations
Brackets				
Polycrystalline alumina (PCA)	Clarity Advanced [a]	0.018 × 0.025	25 non-repeated tests for each wire angulation [c] In both dry and wet conditions	225 tests in wet environment, 225 tests in dry environment
Monocrystalline alumina (MCA)	Inspire Ice [b]	0.018 × 0.025		
Stainless Steel (SS)	Victory series [a]	0.018 × 0.025		
Archwires				
Stainless steel	Rectangular arch [b] wire	0.016 × 0.022		
Ligatures				
Elastic	Alastic Easy to tie [a]	0.002		

[a] 3M Unitek, CA, USA. [b] Ormco, CA, USA. [c] Zero,5,and 10 degrees.

the bracket and archwire material, geometry, and the method of ligation. Biological factors are related to the oral environment, such as the presence of saliva and an acquired pellicle.[7]

Ceramic brackets provide multiple advantages, including excellent biocompatibility, hardness, colour stability, and resistance to wear and deformation in the oral environment. In addition, their superior aesthetic property meets the cosmetic needs of adults.[8,9] However, despite manufacturers' efforts to improve the physical properties, ceramic brackets still have disadvantages, such as abrasion of opposing enamel surfaces,[10] low fracture toughness, problems with debonding, and high FR.[11] Ceramic brackets have been known for inferior frictional characteristics compared with stainless steel brackets.[11-13] This drawback has led to the development of multiple products that seek to improve frictional characteristics through different refinements.[14,15] As new ceramic brackets are being introduced, there is a need to verify manufacturer claims. The present study therefore aimed to test the static frictional resistance during sliding tooth movement associated with newly-introduced polycrystalline alumina ceramic brackets (PCA) characterised by slots coated with yttria-stabilised zirconia, in contrast with monocrystalline alumina ceramic (MCA) and stainless steel (SS) brackets. The surface topographical features of the tested brackets were also assessed.

Materials and methods

Sample description

A total of 450 as-received brackets were examined in the present study. The test groups included PCA (Clarity Advanced, 3M Unitek, CA, USA) and MCA (Inspire Ice, Ormco, CA, USA), and conventional stainless steel brackets served as a control group (Victory Series, 3M Unitek, CA, USA). All brackets were for the maxillary right bicuspid and possessed a 0.018 × 0.025 inch slot dimension. The prescription for the brackets was standardised with -7° torque and 0° tip. Straight 0.016 × 0.022 inch stainless steel wire alloy (Ormco, CA, USA) was used with all of the bracket types (Table I). Twenty-five non-repeated tests of all groups were carried out in both wet and dry environments at angulations of 0°, 5°, and 10°, each using a universal testing machine (Instron 5965, Instron Corp, MA, USA). A new bracket and wire segment was used for each test, and therefore, a total of 75 new brackets were required for each type in both environments. Elastomeric ligatures (3M Unitek, CA, USA) were used to tie the wires into the brackets. All of the tests were performed by the same examiner.

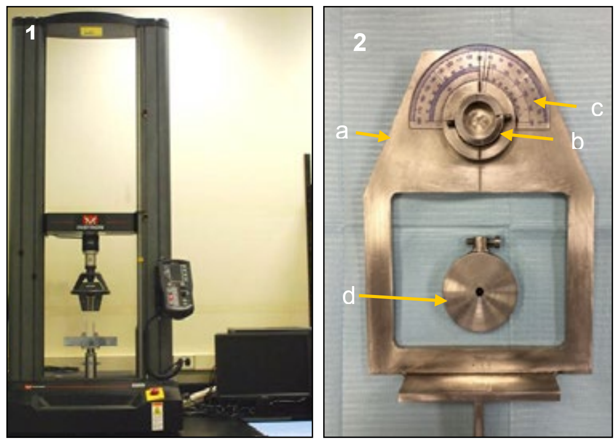

Figure 1. Photographs showing (1) Universal testing machine (Instron 5965), (2) Custom made mounting device. (a) Outer Aluminum block. (b) Inner holder. (c) Protractor. (d) 150 g weight.

Experimental setup

To take second order bends into account while testing frictional resistance, a special testing device was constructed and attached to the Universal Testing Machine (Figure 1). The device was modified from a method used previously[16] and consisted of an outer aluminum block, with a height of 20 cm and width of 15 cm, attached to an anterior-posterior adjustment base, which stabilised the device in the Instron testing machine. The outer block surrounded an inner round holder in which the specimens holding the bracket-wire assembly were attached. The inner holder was adjustable to the three angulation guides (0°, 5°, 10°) placed on the outer block using a protractor.

The straight as-received 0.016 × 0.022 inch stainless steel wires were cut into 20-cm-long segments and cleaned of any possible debris with 95% ethanol. Each wire was ligated to the bracket bonded to the corresponding tooth duplicate by elastomeric modules. A 150 g weight was fixed to the wire's lower end to maintain tension. The test drew the archwire upward through the bracket slot at a cross-head speed of 5 mm/min for two minutes. Computer software associated with the Instron machine recorded the FR generated between the bracket and the wire on an XY graph. The X axis recorded wire movement in millimeters per second, and the Y axis recorded the FR force between the bracket slot and the archwire. The static frictional force was obtained as the peak force encountered during the first millimeter of wire displacement in the load-displacement graph. Twenty-five non-repeated tests were carried out for each bracket type at the three wire angulations. A total number of 225 tests were performed in a dry environment at room temperature.

An additional set of 225 specimens was prepared for the wet environment test as previously described. An artificial saliva solution was formulated and, after ligating the wires into the brackets, the specimens were soaked in the saliva solution for 48 hours at 37°C in a Memmert Universal Oven (Memmert Edestahl, Rost Feri, Germany) as a modification of the method reported in a previous study.[17] Thereafter, the archwire sliding test was carried out as before. A plastic syringe (Terumo Syringe, Laguna, Philippines) was filled with 7 ml of artificial saliva solution at 37°C and used to constantly bath the brackets during the test at a rate of one drop/second.

Scanning electron microscope analysis (SEM)

A scanning electron microscope (SEM) (JSM 6360LV, JEOL Ltd, Tokyo, Japan) was used to evaluate the three types of brackets and obtain a qualitative morphological evaluation of the slot surfaces before the archwire sliding tests. An as-received bracket of each type was randomly selected and prepared for scanning by coating with gold foil using a Fine Coat machine (Ion Sputter JFC-1100, JEOL Ltd, Tokyo, Japan) for three minutes. The brackets were scanned by an SEM using high vacuum-chamber pressure at 10 kV. Two photomicrographs were taken of each bracket type for the overall and inner slot evaluation at 22× and 1000× magnification, respectively.

Optical profilometer analysis

Twenty-five brackets of each type were randomly selected and subjected to surface topography analysis before running the archwire sliding tests. Each bracket specimen was numbered in a way that permitted the correlation of its calculated roughness values with the frictional force values obtained in the 0° wire angulation (dry environment). The surface topography measurements were performed using an optical non-contact surface profiling system (Bruker Contour GT-K, Bruker nano GmbH, Berlin, Germany) based on non-contact scanning white light interferometry to evaluate the 3D surface configuration and roughness of each bracket slot surface. The machine was placed on a vibration isolation table in a super-silent room. The test area chosen for each bracket was on the disto-gingival side of the slot surface. The profilometer-scanned area was approximately 1.3 × 1.0 mm^2 using an objective standard camera at 5× magnification. The data were processed using Vision 64 application software (Bruker Contour GT-K, Bruker nano GmbH, Berlin, Germany) to control the precision and measurements of the surface roughness parameters. Five surface roughness parameters were determined and included the arithmetic average height of the surface topography, also known as average roughness (Sa); root mean square of the surface topography (Sq); ten-point height of the surface topography (S_s); skewness of topography height distribution (Ssk); and kurtosis of topography height distribution (Sku). After measurement, the friction force measurement test was performed on the brackets in the 0° wire angulation. The results of the frictional force test were correlated with the results of the two roughness parameters, average roughness value (Sa) and root mean square of surface topography (Sq).

Statistical analysis

A statistical analysis was undertaken using IBM SPSS software (IBM SPSS Inc., version 20, IL, USA), and the level of significance for all tests was set at $p < 0.05$. With the chosen sample size of 25 per group, a minimum statistical power of 0.80 was estimated for each two-sided comparison. Normal distribution of the data was tested for each group comparison using the Kolmogorov-Smirnov test, and Levene's test was used for homogeneity of variance. Parametric tests were applied for all group comparisons, even when the normality or homogeneity was not satisfied according to the central limit theorem and was based on the sample size of each subgroup. In the dry and wet environments, the overall RS between bracket materials (regardless of bracket-wire angulation) and the overall RS among wire angulations (regardless of bracket material) were compared using one-way ANOVA followed by Tukey's post hoc test. Pearson's correlation test was used for the correlation of the RS values with the degree of the bracket slot-wire angulation in both the wet and dry environments. The effect of the test environment (either dry or wet) on the RS for each bracket type was compared using the student's *t*-test. The measurements of the roughness parameters were compared using one-way ANOVA followed by Tukey's post hoc tests. The correlation between the roughness parameters and RS at 0° wire angulation (dry environment) was tested using Pearson's correlation coefficient.

Results

In the dry environment, the comparison of the overall FR between the bracket groups showed that MCA ceramic brackets had the highest FR values, followed by SS and then PCA brackets. A comparison of the mean values revealed significant differences between the MCA and the SS and PCA bracket groups ($p < 0.001$), while no significant difference was found between PCA and SS brackets ($p = 0.27$) (Table II) (Figure 2). A comparison of the FR between different wire angulations, regardless of the bracket type, revealed that the highest FR was found at the 10° wire angulation, followed by the 5° and then the 0° wire angulation. The mean values of each angulation group were compared and the results indicated that there were significant differences between each group ($p < 0.001$). Moreover, the FR values were strongly correlated with the degree of the wire angulation (correlation coefficient = 0.85, $p < 0.001$). A comparison of the FR between all bracket groups at one specific wire angulation produced the following results: at 0° and 10° angulations there were significant differences between each bracket type ($p < 0.001$)

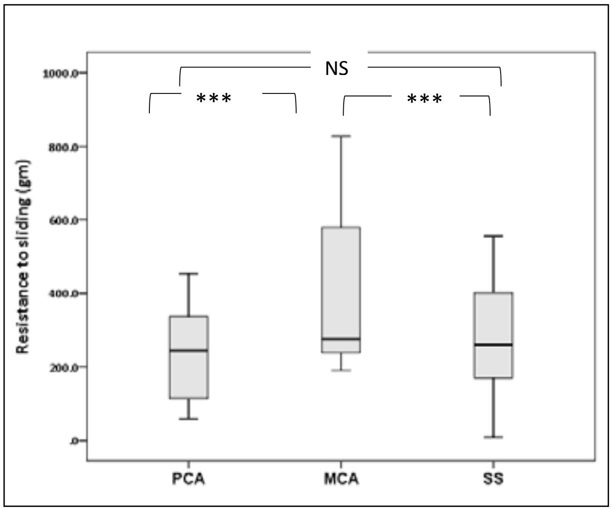

Figure 2. Box plot graph of the overall frictional resistance among bracket groups (dry environment). (PCA) polycrystalline alumina brackets. (MCA) monocrystalline alumina ceramic brackets. (SS) stainless steel metal brackets. NS not significant, $^{***}p < 0.001$.

Table II. Descriptive statistics of the overall resistance to sliding among brackets groups (dry environment). (PCA) polycrystalline alumina. (MCA) monocrystalline alumina ceramic brackets. (SS) stainless steel.

Bracket groups	Descriptive statistics Frictional resistance (gm)				
	Mean	Standard deviation	Confidence interval	Minimum	Maximum
PCA	244	118	217 – 271	59	453
MCA	386***	199	341 – 431	191	827
SS	283	137	252 – 315	9	555

*** $p < 0.001$

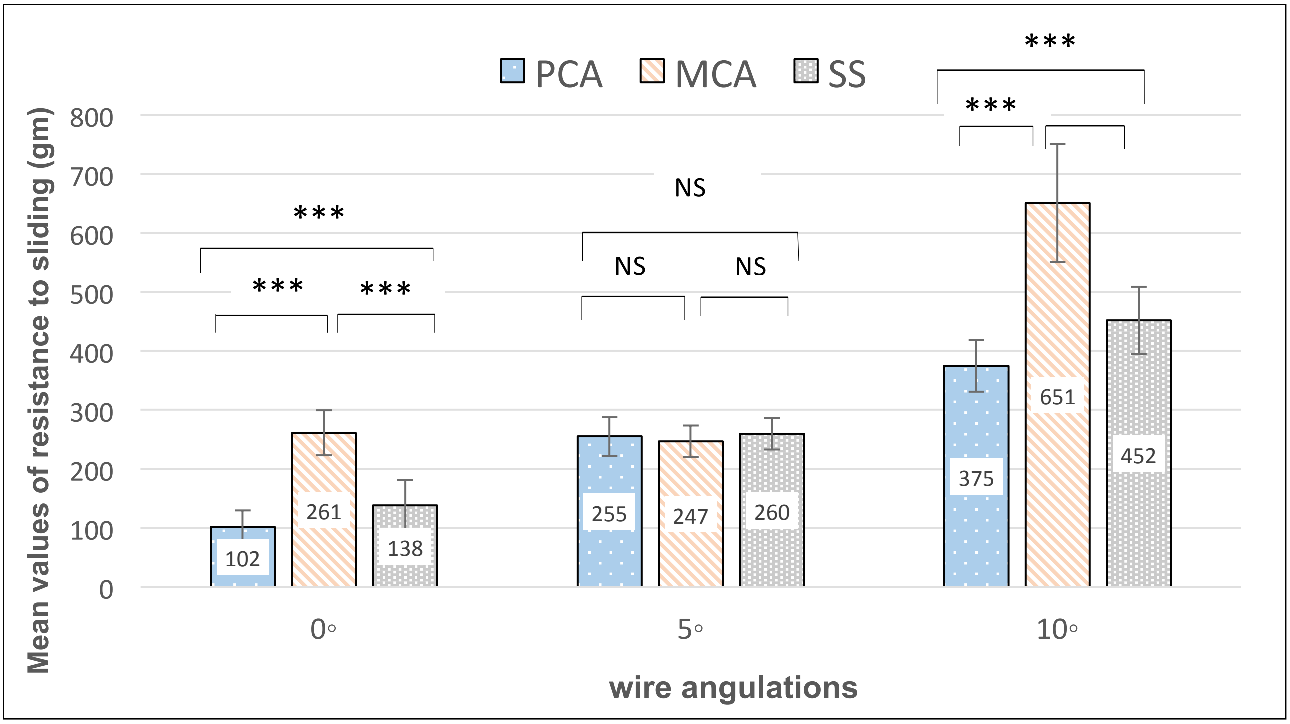

Figure 3. Bar graph of the comparison between mean values of frictional resistance among bracket types in all three wire angulations (dry environment). (PCA) polycrystalline alumina brackets. (MCA) monocrystalline ceramic brackets. (SS) stainless steel brackets. ***$p < 0.001$.

Table III. Descriptive statistics of the overall frictional resistance among brackets groups (wet environment). (PCA) polycrystalline alumina. (MCA) monocrystalline alumina. (SS) Stainless steel.

Bracket groups	Descriptive statistics Frictional Resistance (gm)				
	Mean	Standard deviation	Confidence interval	Minimum	Maximum
PCA	352	196	307 – 397	60	640
MCA	349	136	317 – 380	106	623
SS	317	192	272 – 361	58	741

and at the 5° angulation there were no significant differences between the bracket types (Figure 3).

A comparison of the overall wet environment FR mean values revealed that the highest value was found in the PCA bracket group, followed by MCA and then SS brackets. However, no significant differences were found between these groups (Table III) (Figure 4).

An evaluation of the photomicrographs indicated that the slot surface of the SS brackets appeared to be the smoothest, followed by the polycrystalline alumina ceramic brackets (PCA), whereas the slot surface of the monocrystalline alumina ceramic brackets (MCA) appeared to be pitted and filled with surface impurities. The designs of the slot outer corners (bevel areas) were also assessed and the PCA ceramic brackets had the roundest corners, whereas SS and MCA brackets had similar sharp slot corners. The edges of the MCA bracket slots were rough and slightly jagged (Figure 5).

The PCA ceramic brackets scored the highest mean value for the S_a roughness, followed by SS and then MCA ceramic brackets. The differences were significant between all the bracket types ($p < 0.001$) (Figure 6). A comparison of the mean values revealed no significant differences between the bracket groups for S_s roughness. A comparison of the mean values revealed that MCA ceramic brackets had significantly higher S_{ku} roughness values than PCA ceramic brackets ($p = 0.04$) and were not significantly different from SS brackets. No significant difference was found between SS brackets and PCA brackets. There was no significant correlation between the FR values

Table IV. Correlation between frictional resistance and average roughness (Sa) parameter of the brackets. (PCA) polycrystalline alumina. (MCA) monocrystalline alumina. (SS) stainless steel.

	Brackets		
	PCA	MCA	SS
Pearson correlation coefficient	- 0.009	- 0.037	0.39
P value	0.96	0.86	0.06

Table V. Correlation between frictional resistance and root mean square (Sq) parameter of the bracket types. (PCA) polycrystalline alumina. (MCA) monocrystalline alumina. (SS) stainless steel.

	Brackets		
	PCA	MCA	SS
Pearson correlation coefficient	- 0.102	0.22	0.213
P value	0.63	0.3	0.31

for any of the brackets and their corresponding slot average roughness values (Table IV). There was no significant correlation between the FR values for any of the brackets and their corresponding slot root mean square values (Table V).

Discussion

Although the term 'friction resistance' is most frequently used to represent the force resisting the sliding movement of the teeth, the resistance to sliding (RS) can be divided into three phenomena: classic friction (FR), binding (BI), and notching (NO), generally written as RS=FR+BI+NO.[3] Classic friction occurs between brackets and the archwire when there is clearance between their surfaces. This happens when the archwire is in a passive configuration without angulation, inside the bracket slot. Binding occurs in the active wire configuration when the clearance between the wire and the bracket slot disappears and the wire contacts the bracket corners. The angle at which FR no longer exists and the binding dominates is called the critical angle (Φc). Notching happens when the sliding movement is impeded by the presence of a permanent wire deformation at the bracket-wire interface following a severe binding incident.[3] High FR in fixed orthodontic appliances can result in the dissipation of the majority of the applied force delivered for tooth movement. Control of the FR generated between the bracket slot and the archwire is a crucial element in achieving efficiency of the sliding movement during the space closure stage of orthodontic treatment. Bracket materials remain one of the most important parameters that affect FR in fixed orthodontic appliances.

Ceramic brackets have long been known to be inferior to metal brackets in their frictional characteristics.[11] Therefore, manufacturing companies have been working to improve these characteristics to optimise clinical performance while maintaining the aesthetic appearance of the appliances. The brackets of choice in the present study were a previously-available MCA ceramic bracket and a newly introduced PCA ceramic bracket that is characterised by yttria-stabilised zirconia coating of the slot. To the best of current knowledge, this type of PCA ceramic bracket has not been tested previously.

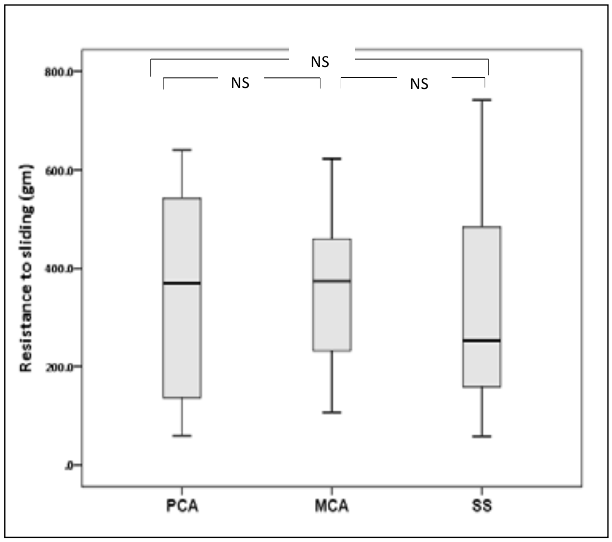

Figure 4. Box plot graph of the overall frictional resistance among bracket groups (wet environment). (PCA) polycrystalline alumina ceramic brackets. (MCA) monocrystalline alumina ceramic brackets. (SS) stainless steel. NS not significant.

The results of the present study in a dry environment indicated that the highest FR was found in the MCA ceramic bracket group. Furthermore, there was no difference between the PCA and SS brackets. These findings are in agreement with several previous studies that reported higher frictional forces associated with MCA ceramic brackets compared with conventional PCA or SS brackets.[18-22] Most of the investigators, however, attributed the results to the differences in surface roughness between the SS and ceramic brackets. The quantitative assessment of the roughness values in the present study indicated that the MCA brackets were the smoothest, followed by the SS brackets, and the

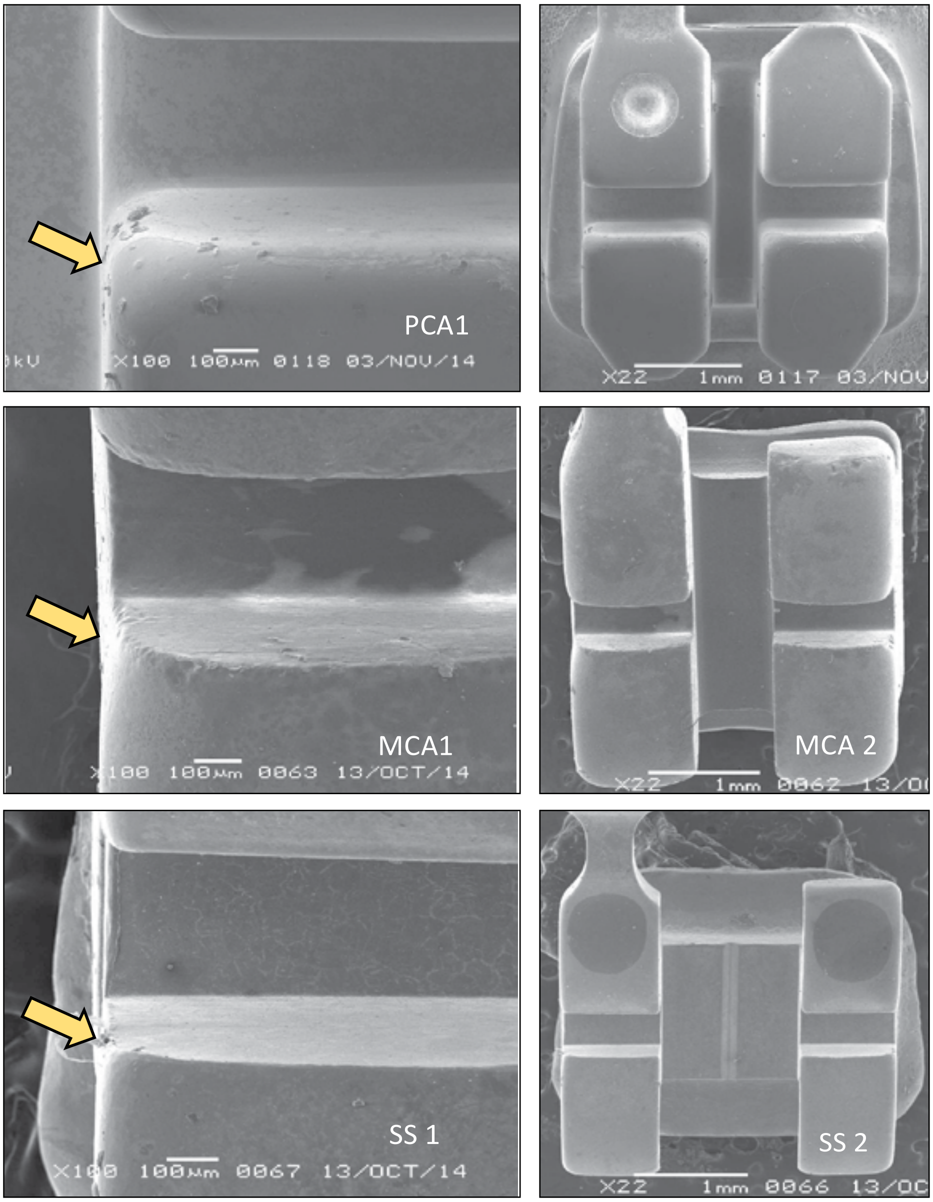

Figure 5. Photomicrographs obtained by scanning electron microscope. (1) Close-up view of the slot areas. (2) Overall view of the bracket design. (PCA) Polycrystalline ceramic brackets. (MCA) Monocrystalline ceramic brackets. (SS) Stainless steel metal brackets. Arrows pointing to 'bevel area' of the slots.

PCA brackets. The relationship between the bracket surface roughness and the frictional characteristics has not been equivocally defined. Cha et al.[23] evaluated the surface roughness of the studied brackets using a scanning electron microscope and found that the MCA ceramic brackets, of the same type used in the present study, had the smoothest slot surface, although they recorded the highest frictional force in most of the bracket-wire angulations examined. In a recent study by Choi et al.,[24] quantitative measurements were taken of the slot surface roughness of the included brackets. Interestingly, the same type of MCA brackets used in the present study had the smoothest slot surface and scored the highest friction values. Saunders and Kusy[25] measured the surface roughness of the bracket slots using laser specular reflectance and found that MCA ceramic brackets were significantly smoother than the conventional PCA ceramic brackets; however, there was no difference in their frictional characteristics. The justification provided by these studies could also be applied to the present study. The MCA ceramic brackets had sharp and hard edges formed by the intersection of the floor and the side walls of the slots. These characteristics exacerbated the binding

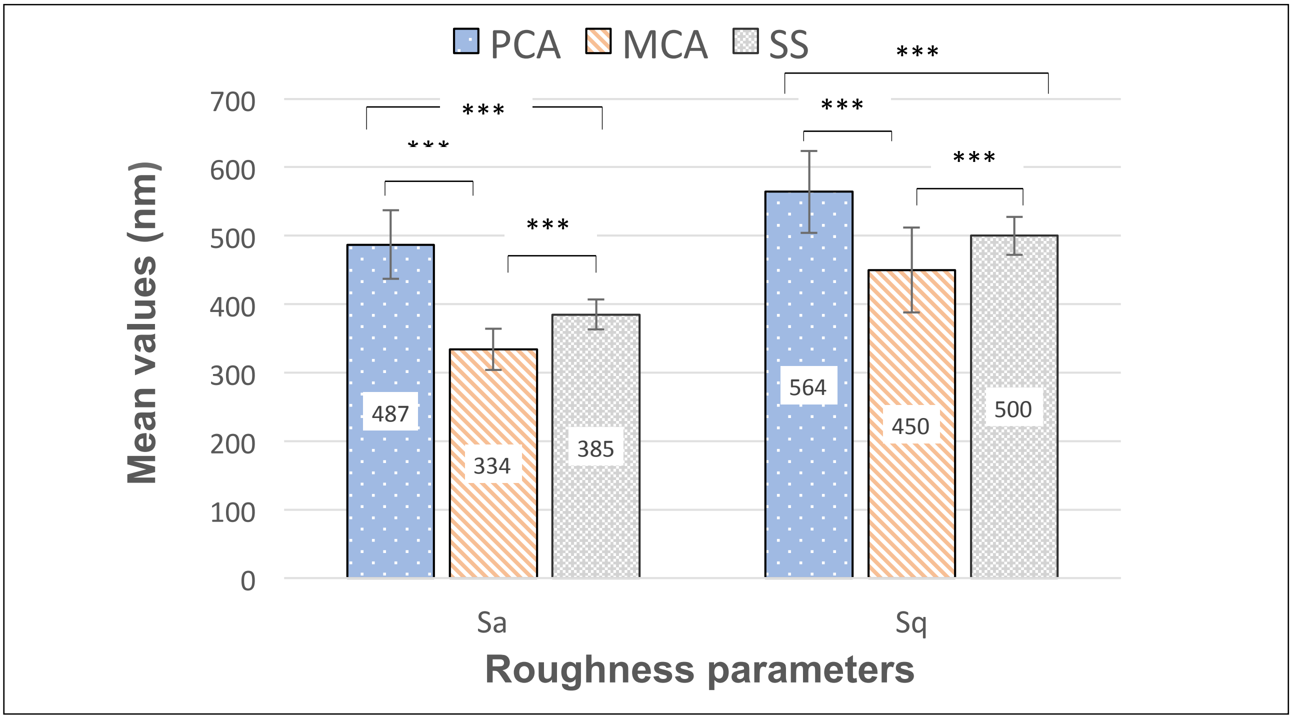

Figure 6. Bar graph comparing average roughness (Sa) and root mean square (Sq) among bracket groups. ***$p < 0.001$.

between the archwires and the bracket corners and may have negated any positive role contributed by their smoother surfaces, if present. It has been found that the design of the bracket slot corners seen in the PCA bracket tested in the present study, or the so-called 'bevel', can significantly reduce the frictional resistance of the bracket. As the area of the bracket bevel reduces and the corners become sharper, the FR increases[14] due to the reduction in the critical contact angle at the bracket slot-wire interface, which means more binding.[15] Articolo and Kusy[5] reported that the highest percentage of binding, which reached 99%, was found by force couples between SS archwires and MCA brackets. Regardless of the hypothesised reasons for the higher FR in MCA ceramic brackets, it seems from the current literature that MCA brackets have rarely been found to have less FR than PCA ceramic brackets.[26] The majority of the previous investigations reported either no significant differences between MCA and PCA brackets[25,27] or higher FR values in MCA compared with PCA brackets.[19,20,23] The results of the present study revealed no significant differences between the newly-introduced, slot-coated PCA ceramic brackets and SS brackets in overall FR values. Only a few studies have reported no significant difference in FR when comparing conventional PCA brackets with SS brackets;[28-30] however, the results cannot be considered comparable with the present findings because the adopted study models did not include a binding component of FR. The majority of the studies demonstrated higher FR in PCA ceramic brackets compared with metal brackets. This finding was attributed to the significantly rougher surfaces associated with PCA ceramic brackets.[13,23,24,27,31] The PCA ceramic brackets used in the present study scored the highest roughness value of all brackets, whereas their frictional characteristics did not differ significantly from the SS brackets. This finding supports the hypothesis that surface roughness may not play an important role in the frictional characteristics of the brackets.

To the best of current knowledge, the type of PCA bracket used in the present study is new and no previous research has tested its frictional characteristics. It has been reported by the product's developers that it is the first of its type to have a low friction coating on the slot surface that is based on yttria-stabilised zirconia (YSS) deposited via radiofrequency (RF) magnetron spluttering. Using a sliding test, the development team tested the frictional forces of the YSS-coated ceramic against the SS brackets and compared those results with the frictional forces observed in a test of uncoated ceramic against the SS brackets. The YSS-coated ceramic disks registered a lower coefficient of friction (COF) against the SS brackets during the sliding tests than the uncoated ceramic disks. It was reported that the COF of YSS-coated ceramics was comparable with the COF of SS on the SS sliding test. In addition to having a lower COF, it was reported that the coating was also abrasion resistant, smooth, and translucent.[32]

Pure zirconia is a polymorphic material that occurs in three phases: monoclinic (m), tetragonal (t) and cubic (c). By adding stabilising oxides such as yttrium oxide (Y_2O_3), zirconia can be stabilised in the more durable tetragonal phase at room temperature. The integrity and durability of the YSS-coating in the bracket slots could be based on a phenomenon called 'transformation toughening'. This tetragonal (t) to monoclinic (m) phase transformation can be induced by external stresses, which could include the sliding process in the case of brackets and archwires. These external stresses lead to the development of internal stresses that oppose crack propagation and eventually toughen the surfaces. The superior mechanical properties, including the high fracture toughness of yttrium-stabilised zirconia, make this material uniquely closer to stainless steel than all other types of ceramics.[33] It is possible that the similarity of the mechanical properties of YSS and SS might have played a role in approximating their frictional properties. It has been hypothesised that there are other physical properties that raw materials should possess for bracket manufacturing apart from roughness values, such as adequate hardness, stiffness, and compressive yield strength.[34] The hardness of the bracket materials has been ranked in a descending order from MCA as the hardest, followed by PCA, and then SS.[5] This ranking could explain the present findings and might indicate a direct relationship between hardness and frictional resistance.

When the FR of the brackets was compared with one wire angulation (dry environment), the general ranking was maintained for all angulations, with the MCA ceramic brackets as the highest, followed by SS brackets and then PCA brackets in descending order. However, at the 5° angulation, there was no significant difference between the bracket groups. This finding might suggest that in relation to the FR in the passive configuration, the binding stage has the same significant effect of increasing the FR regardless of the bracket type. The abrupt and substantial increase in FR at the highest wire angulation (10°) in all bracket types might be caused by notching of the archwire against the bracket corners, as proposed by Thorstenson and Kusy.[15] Although the MCA ceramic brackets had the highest overall FR and the highest increase at 10°, they had a smooth transition, as indicated by the FR from the passive wire configuration to the initial binding stage at 5°. This finding was also reported by Cha et al.[23] for the same type of MCA ceramic bracket used in the present study. It is suggested that this finding was a result of the differences in the ranges of critical angle of each bracket type. It is possible that the type of MCA brackets used had a higher critical angle range than the other types. However, such an assumption cannot be confirmed from the present study and further investigation is needed to compare the critical angles of different bracket types, an approach previously suggested by Kusy and Whitley.[35] SEM observation in the present study indicated that the MCA ceramic brackets had sharp slot corners, which may be responsible for the highest FR encountered. The PCA ceramic bracket was the only type to show bevelled corners in the SEM evaluation. It seems that this feature, coupled with the low friction coating of YSS, might be the reason this type of bracket approximated the behaviour of the SS bracket, which is considered the gold standard in brackets.[3]

The rank of the overall FR among the three bracket groups changed slightly in the wet environment compared with the dry environment. The PCA ceramic brackets had the highest FR value, followed by MCA brackets, and then SS brackets. However, these differences were not significant. This finding is supported by the assumption of Smith et al.,[36] who suggested that the rank order of the FR of the materials did not significantly change with the use of a lubricating medium.

Scanning electron photomicrographs provided a general assessment of the bracket slot surfaces and geometrical features. The SS bracket surfaces appeared to be the smoothest, followed by the PCA brackets and MCA ceramic brackets. The present study's SEM findings regarding the MCA ceramic brackets were in agreement with those of Angolkar et al.,[37] who examined the same type of MCA brackets via SEM and found their surfaces filled with generalised indentations compared with the SS brackets. This was attributed to the technical difficulties associated with the manufacturing process of this type of MCA ceramic bracket. Despite this, with the advancement of surface topography characterisation techniques, this subjective evaluation of the surfaces' general appearance is not conclusive and cannot definitively reflect the surface roughness value. Therefore, a quantitative method of roughness measurement was executed using a non-contact optical profilometer. According to the most commonly used roughness parameters, Sa and Sq, the results indicated that the lowest roughness values were registered in the MCA bracket group, followed by the SS group and PCA group in descending order. In contrast, the roughness rank order of the bracket groups was not consistent with their SEM appearance, which stresses the uncertainty of the SEM results. The degree of slot surface smoothness is not likely to be related to the frictional characteristic performances during sliding movement. This finding is supported by previous studies and by the present study that indicated a non-significant correlation between the average roughness values of the bracket slot and the friction resistance values. Although that correlation was not significant, it is proposed that the negative relation between the bracket slots and the frictional resistance in some groups might shed light on the question of how much bracket slot smoothness is sufficient for enhancing sliding movement. It is possible that the extra smoothness of the surfaces might be negatively reflected in FR during sliding. Prososki et al.[38] proposed that friction tends to be greatest for very rough or very smooth surfaces. Very smooth areas provide larger areas for adhesion, which increases the resistance of sliding between two surfaces. Nevertheless, this assumption needs to be validated by further controlled investigations in the field of tribology and material sciences, especially because none of the previous studies have statistically correlated bracket slot roughness and frictional resistance. It has been stated that to correlate the friction forces with roughness values, surfaces with well-structured topographies and statistical roughness should be prepared in a controlled method.[39]

Conclusions

The YSS coating of the PCA ceramic bracket slots, in addition to the bevelled corners, might be a successful approach to reproduce the frictional characteristics of SS brackets. For all the bracket groups tested, there was a direct relationship between the bracket slot-wire angulation and the FR in both environments. This finding signified the importance of a proper levelling and the alignment stage before proceeding to the tooth retraction phase using sliding mechanics. The PCA brackets had the highest roughness values for parameters Sa and Sq, followed by SS and then MCA brackets. There was no significant correlation between the slot average roughness values and the frictional resistance. Therefore, the smoothness of the slot surface does not seem to play an important role in the reduction of frictional resistance.

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